4. MATERIALS FOR AIR HANDLING, HOT SECTION, AND STRUCTURAL COMPONENTS

A. High-Temperature Advanced Materials for Lightweight Valve Train Components

Jeremy S. Trethewey, Principal Investigator
Mark Andrews, John Grassi, David Longanbach, and Matt Fletcher
Caterpillar Inc.
Tech Center 854-80 TC-E
14009 Old Galena Rd.
Mossville IL, 61552
(309) 578-0056; fax: (309) 578-2953; e-mail: trethewey_jeremy_s@cat.com

DOE Technology Development Area Specialist: Sidney Diamond
(202) 586-8032; fax: (202) 586-1600; e-mail: sid.diamond@ee.doe.gov
ORNL Technical Advisor: D. Ray Johnson
(865) 576-6832; fax: (865) 574-6098; e-mail: johnsondr@ornl.gov

---

Contractor: Oak Ridge National Laboratory, Oak Ridge, Tennessee
Prime Contract No: DE-AC05-00OR22725
Subcontractor: Caterpillar Inc., Peoria, IL

Objective

- Design and fabricate prototype engine valves from silicon nitride and titanium aluminide (TiAl) materials that are 30% lighter than steel valves and provide a 200% increase in service lifetime and a 10% increase in fuel efficiency.

Approach

- Select γ-TiAl and silicon nitride materials for this project because of their high corrosion resistance and ability to maintain superior strength at elevated temperatures.
- Use an optimization routine in conjunction with a probabilistic approach to design valves (although the traditional deterministic method is practical for traditional metals, a probabilistic approach is necessary for high-hardness materials).
- Develop welding techniques to join TiAl to a titanium alloy in the fabrication of TiAl valves.
- Perform bench tests and engine tests to verify the robustness of valve design.

Accomplishments

- Successfully optimized friction welding between TiAl valve heads and Ti-6V-4Al valve stems.
- Conducted bench tests on silicon nitride valves with varying quality of surface finish; valves with good surface finish performed well and valves with poor surface finish failed in an anticipated mode.
- Completed flexure testing of silicon nitride material specimens with different finish machining parameters; results yielded Weibull moduli between 10 and 25.

Future Direction

- Perform bench tests on finish-machined silicon nitride engine valves; then perform engine testing in collaboration with the National Transportation Research Center.
- Procure additional valve blanks and flexure specimens from a second supplier; finish-machine, bench test, and engine test to evaluate strength and durability.
- Continue developing ceramic valve life prediction model using results from bench tests as input.

Introduction

Valve train components in heavy-duty engines operate under high stresses and temperatures and in severely corrosive environments. Advanced ceramics and emerging intermetallic materials are highly resistant to corrosion and oxidation and possess high strength and hardness at elevated temperatures. These properties are expected to allow higher engine operating temperatures, lower wear, and enhanced reliability. In addition, the lighter weight of these materials (about 1/3 that of production alloys) will lead to lower reciprocating valve train mass that could improve fuel efficiency. This research and development program is an in-depth investigation of the potential for use of these materials in heavy-duty engine environments.

The overall valve train effort will provide the materials, design, manufacturing, and economic information necessary to bring these new materials and technologies to commercial realization. With this information, component designs will be optimized using computer-based lifetime prediction models and validated in rig bench tests and short- and long-term engine tests. After proof of concept is established with valves, this design approach will be applied to other components made from high-temperature materials.

Approach

In an effort to develop the tools necessary to design effectively with high-strength, lightweight, brittle materials, a three-pronged approach was adopted. First, computational analysis was performed to optimize thermal and mechanical stresses within the valve during operating conditions. This initial design was cast into silicon nitride and TiAl valve blanks by several suppliers. The second phase of this approach is a characterization effort intended to evaluate valve performance on rig tests and engine tests. Third, a parallel path of study investigating the effects of damage caused by various machining techniques is being pursued. In order to minimize the probability of a brittle failure caused by surface defects, optimal surface finish must be achieved.

Work reported in the FY 2003 report outlines the design process used to adapt the current baseline metallic valve design to a design more suited for a ceramic material. For example, the head dimensions were changed to reduce the stress concentration experienced in the fillet radius. Several silicon nitride valve blanks were procured and finish-machined to these specifications. Because of the high cost of TiAl, only the heads of the valves were cast and finish-machined. After rough machining, the TiAl heads were successfully friction-welded to cylindrical stock of a titanium alloy (Ti-6V-4Al). Subsequently, they will be finish-machined before rig and engine testing.

Results

The mechanics of a structural brittle material are inherently different from those of a traditional metal. Whereas a metal (current-production valve material) may be adequately modeled as a continuum material, a brittle material (proposed valve material) is susceptible to microscopic flaws or cracks. A primary failure mode of a structural ceramic is the propagation of a surface crack initiated during machining. Therefore, it is imperative to understand the influence of various machining parameters on material strength and reliability.

Two types of valves were bench tested with a motor-driven valve impact rig: valves with a good surface finish (NT551 material) and a valve with a poor surface finish (SN235P material). Several NT551 valves survived 1000-hour rig tests incurring minimal damage (Figure 1). However, there appear to be engine deposits on the fillet radius and on the contact regions (composition and nature of the deposits has not yet been determined).

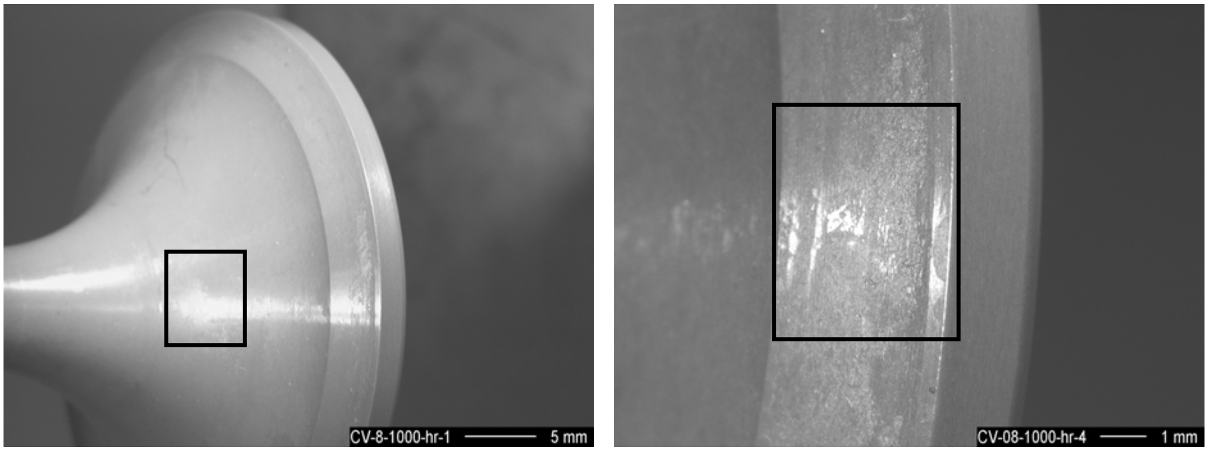

Figure 1. NT551 engine valves subject to 1000 hours of impact / wear tests. Note the deposits in the fillet radius and the contact regions (boxed regions)

In contrast to the good performance of the valves with acceptable surface finish, the performance of a poorly finished valve (SN235P material) was less than acceptable. This does not imply a difference in the quality of the materials but rather the importance of proper machining and surface finish. The keeper groove was not finished to specification, resulting in a rough surface with significant microcracking. Within one hour of rig testing, the valve fractured at the keeper groove. Microscopic analysis indicated that the fracture origin coincided with the region of severe machining damage (Figure 2). Nondestructive analysis performed by J. G. Sun at Argonne National Laboratory confirmed that the failure was a result of a pre-existing surface defect (Figure 3). Note that the white line corresponds to the location in the keeper groove where the flaw originated.

It was therefore decided to discontinue the bench rig testing until the appropriate surface finish was provided for all portions of the valve. The result of a subsequent investigation suggested that there may be an unacceptably low static friction coefficient between the valve and the keeper locks, resulting in a misapplication of the load from the valve spring. A study was launched to determine if the frictional force is inadequate for this application.

To further investigate the importance of surface finish to material strength, an optimization study was performed on cylindrical material (SN235P) flexure specimens with varying machining parameters. The test specimens (8 mm diam × 75 mm length) were subjected to three different finishing machining processes before they were strength-tested in four-point flexure. The tests were conducted at the Oak Ridge National Laboratory (ORNL) through a facility user agreement. A specialized four-point test fixture was designed and built for the cylindrical test specimens by A. Wereszczak of ORNL. All tests were conducted at ambient temperature conditions at the displacement rate of 0.5 mm/min, as specified in the ASTM C-1161 standard.

Figure 4 shows the characteristic strength and uncensored Weibull moduli of 12 different surface finish conditions. The characteristic strength shown in Figure 4 suggests that the inherent strength of the SN235P material is met regardless of machining condition. However, it is apparent that some of the finishing processes improve the data variance, as indicated by the high Weibull modulus values in Figure 4. A plausible explanation for the increase in the Weibull modulus values is that some finishing processes induce an appreciable compressive residual stress while others do not. The fractured samples will be examined using X-ray diffraction at ORNL to investigate the role of residual stress in the materials' strength behavior.

Conclusions

An investigation into the use of advanced materials for valve train applications is under way. The three-pronged approach combines probabilistic design techniques, rig and engine testing, and a systematic study of the effects of machining damage on reliability material. Rig testing exposed the importance of generating components with low-defect sur-

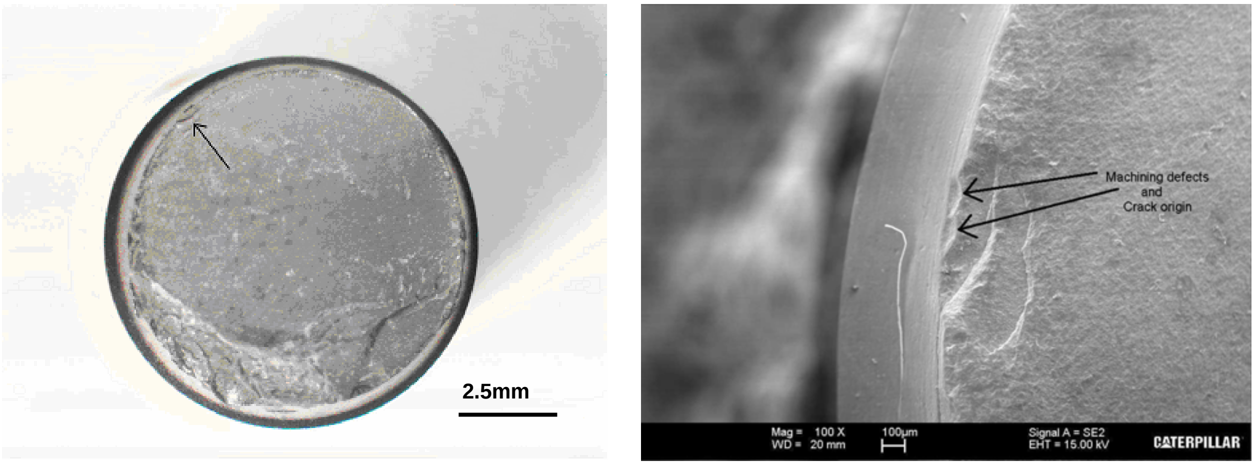

Figure 2. Fracture surface from fractured SN235P valve keeper groove observed from axial view: (left) optical micrograph, (right) scanning electron microscope image.

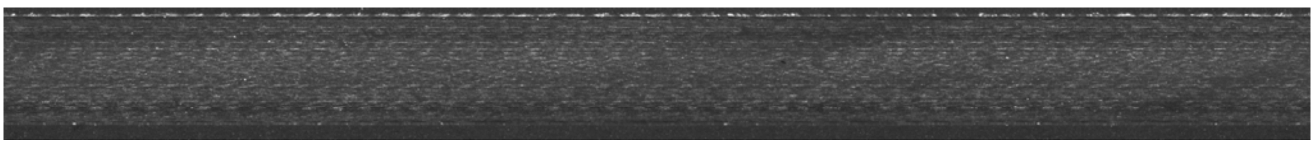

Figure 3. Laser scanning nondestructive evaluation image of the keeper notch of a poorly finished SN235P valve, showing a line of possible machining damage at the top of the image.

faces, and a study examining the effect of machining conditions on identical material specimens reached the same conclusion.

In addition to this fundamental study, several other steps will be taken to further examine the feasibility of fabricating a commercially viable ceramic or intermetallic valve. Arrangements are being made to engine test the silicon nitride valve prototypes near ORNL. Also, a new test rig will be rebuilt that will allow examination of both thermal and mechanical effects on experimental valves; and a more detailed life prediction model will be developed to examine the effect of accumulated damage on ceramic and intermetallic valves. Present and future efforts will help establish an understanding of how to design and manufacture nontraditional lightweight materials for valve train and other heavy-duty diesel engine applications.

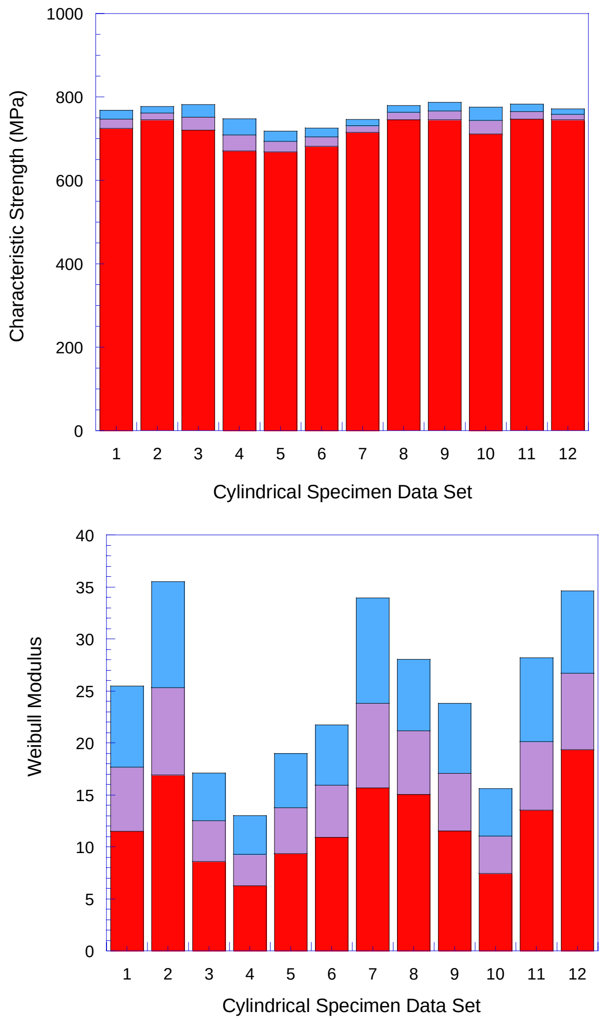

Figure 4. Results from four-point flexure test of SN235P cylindrical test specimens for various finish machining conditions: (top) uncensored Weibull characteristic strength; (bottom) uncensored Weibull moduli. Note that regions at the top of each column represent the 95% confidence interval of the data.